

# High-Efficiency Screen Printed Silicon Ribbon Cells Through Process-Induced Enhanced Hydrogenation and Gettering

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## ABSTRACT

A low-cost, manufacturable defect gettering and passivation treatment, involving simultaneous anneal of a PECVD  $\text{SiN}_x$  film and a screen-printed Al layer, is found to improve the lifetime in Si ribbon materials from 1-10  $\mu\text{s}$  to over 20  $\mu\text{s}$ . We propose a three-step physical model, based on our results, in which defect passivation is governed by the release of hydrogen from the  $\text{SiN}_x$  film due to annealing, the generation of vacancies during Al-Si alloying, and the retention of hydrogen at defect sites due to rapid cooling. Enhanced hydrogenation and rapid heating and cooling resulted in screen-printed Si ribbon cell efficiencies approaching 15%.

## 1. Introduction

Although the low-cost growth of Si ribbon samples makes them attractive for photovoltaic substrates, the as-grown minority carrier lifetime is typically in the range of 1-10  $\mu\text{s}$ , which is not suitable for high-efficiency cells ( $\geq 15\%$ ). The aim of this study is to raise the lifetime in low-cost Si ribbon materials to over 20  $\mu\text{s}$  by investigating the combination of  $\text{SiN}_x$ -induced hydrogenation and Al gettering, and to identify any synergism between the two. A physical model is proposed which relates the  $\text{SiN}_x$ -induced hydrogenation to the release of hydrogen into the sample, the injection of vacancies from backside Al/Si alloying, and the retention of hydrogen at defects. Finally, high-efficiency solar cells are fabricated and analyzed to demonstrate the positive synergistic effects of Al-enhanced hydrogenation and RTP.

## 2. Al-enhanced PECVD $\text{SiN}_x$ -induced hydrogen passivation of Si ribbons

Fig. 1 shows the lifetime enhancement in EFG, dendritic web, and String Ribbon Si due to gettering and hydrogen passivation treatments. The lifetime of EFG and dendritic web Si did not increase after PECVD  $\text{SiN}_x$  film deposition and anneal at 850°C in a belt furnace, while the lifetime of String Ribbon showed a moderate increase from 8.3  $\mu\text{s}$  to 12.9  $\mu\text{s}$ . The ~930°C P and 850°C Al gettering treatments improved the lifetime in all three ribbon materials but were unable to raise the lifetimes over 20  $\mu\text{s}$ . To identify any interaction between the Al gettering and hydrogen passivation processes, the  $\text{SiN}_x$ -induced hydrogenation and Al gettering treatments were performed simultaneously at 850°C after the P gettering. The simultaneous anneal of  $\text{SiN}_x$  and Al increased the lifetime in EFG, dendritic web,

and String Ribbon Si to 25.6  $\mu\text{s}$ , 20.0  $\mu\text{s}$ , and 38.4  $\mu\text{s}$ , respectively. The significant enhancement in lifetime achieved after the simultaneous anneal of  $\text{SiN}_x$  and Al indicates that there is a positive synergistic interaction between the  $\text{SiN}_x$ -induced hydrogenation on the front and Al-Si alloying at the back of the sample which enhances the lifetime to over 20  $\mu\text{s}$  in all three materials.

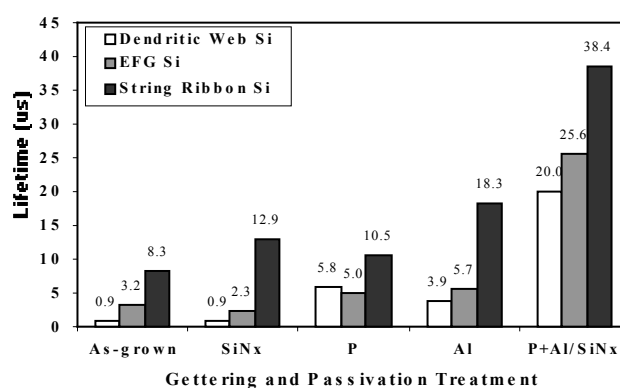


Fig. 1. Al-enhanced  $\text{SiN}_x$ -induced defect passivation in Si ribbon materials.

Fig. 2 shows that the presence of Al on the back of the samples during the anneal shifts of the optimum anneal temperature from 700°C to 825°C and increases the maximum lifetime from 3.2 to 8.3  $\mu\text{s}$ . This improvement in lifetime is much greater than the sum of the improvements due to the individual  $\text{SiN}_x$  and Al treatments for all temperatures above 700°C, indicating that there is a synergistic interaction between the hydrogenation process and Al/Si alloying above 700°C. The increase in the optimum anneal temperature for Al/ $\text{SiN}_x$  above 800°C for lifetime enhancement is also expected to improve the quality of the Al-BSF and hence the cell performance.

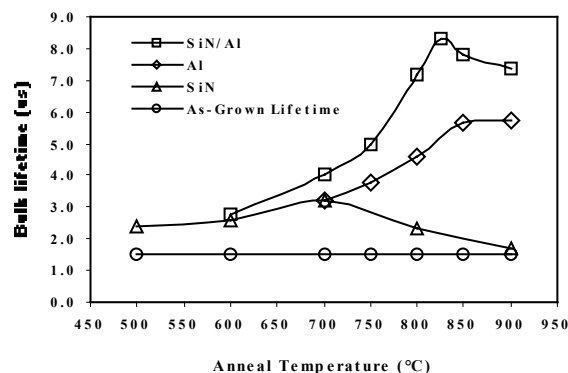


Fig. 2. Optimization of the anneal temperature for Al-enhanced  $\text{SiN}_x$  induced defect passivation.

### 3. Physical Model for Al-enhanced SiN<sub>x</sub>-induced hydrogenation

We propose a three-step physical model according to which defect passivation is governed by the release of hydrogen from the SiN<sub>x</sub> film, the generation of vacancies, and the retention of hydrogen at defect sites in Si. At low temperatures, the effectiveness of the SiN<sub>x</sub>/Al anneal is reduced by the limited release of hydrogen from the SiN<sub>x</sub> film, the low generation of vacancies during Al alloying, and the ineffectiveness of Al gettering. When the anneal temperature is increased to 825°C, vacancies generated in Si during Al/Si alloying, increase the dissociation of molecular hydrogen into atomic hydrogen [1] and enhance the transport of hydrogen in Si. The high binding energy of hydrogen to vacancy clusters (3-4 eV) [2] provides an additional driving force for the diffusion of hydrogen enabling the passivation of defects deep in Si. At temperatures above 825°C, the retention of hydrogen at defects in Si decreases which lowers the lifetime.

### 4. Fabrication and analysis of high-efficiency, screen-printed Si ribbon solar cells by enhanced hydrogenation

Table 1 shows that the average float zone cell efficiency improves by 0.5% (absolute) when the front contacts are fired in the RTP system after the SiN<sub>x</sub>/Al simultaneous anneal at 850°C in the belt furnace. Analysis of the long wavelength IQE showed that RTP contact firing improves the back surface recombination velocity by a factor of two, due to the rapid remelting of Al which improves the uniformity of the Al-BSF. Table 1 also shows that efficiency of EFG and String Ribbon solar cells increase by 1.4% and 1.7% respectively due to RTP front contact firing. Noteworthy high efficiencies of 14.7% (measured by Sandia National Labs.) and 14.6% were achieved on String Ribbon and EFG when contacts were fired in the RTP system. The efficiency enhancement from RTP contact firing of ribbon cells is reflected in improved bulk and surface passivation ( $J_{sc}$  and  $V_{oc}$ ) and contact quality (FF).

Table 1. Impact of RTP front contact firing on 4-cm<sup>2</sup> float zone, EFG, and String Ribbon Si cells.

Contact Firing			$V_{oc}$ (mV)	$J_{sc}$ (mA/cm <sup>2</sup> )	FF	Eff (%)
RTP	Float Zone	Average	621	34.2	0.777	16.5
		High	622	34.3	0.779	16.6
	EFG	Average	573	32.1	0.749	13.8
		High	585	32.8	0.757	14.6
	String Ribbon	Average	574	31.6	0.762	13.8
		High *	600	31.6	0.778	14.7
Belt Furnace	Float Zone	Average	614	33.7	0.770	15.9
		High	615	33.9	0.771	16.1
	EFG	Average	554	30.1	0.743	12.4
		High	566	30.9	0.751	13.1
	String Ribbon	Average	553	29.7	0.738	12.1
		High	575	31.1	0.747	13.4

\* - confirmed by Sandia National Labs.

Fig. 3 shows LBIC scans, made with the *PVSCAN 5000* system using a 905 nm laser, of String Ribbon cells taken from consecutive sections of the ribbon to identify defects and their activity. Note that these samples have similar crystallographic defect structures. The LBIC response in

intragrain regions improved from 0.58 A/W to 0.64 A/W with RTP contact firing as opposed to slow belt firing. Fig. 3 reveals a defect whose activity decreases as the defect extends from Cell 1-3 into Cell 16-1. The cell efficiency data in Table 1 and LBIC analysis in Fig. 3 indicate that RTP firing of screen-printed contacts is more effective in retaining the hydrogen at defects that was introduced during the 850°C Al/SiN<sub>x</sub> anneal. Conversely, the slow ramp rates during belt furnace contact firing result in increased dehydrogenation of defects, increasing their electrical activity.

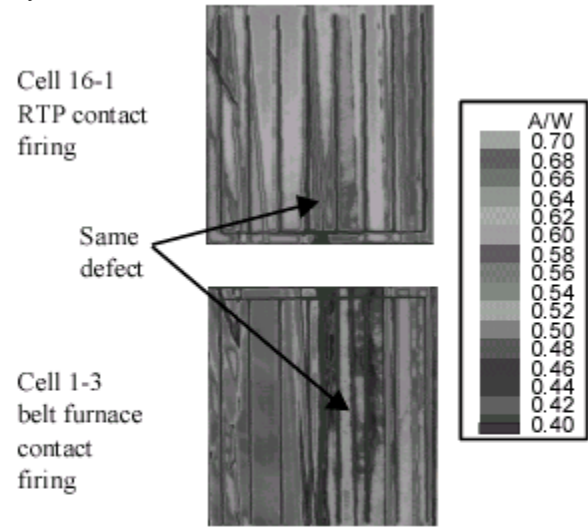


Fig. 3. Improved passivation of intergrain and intragrain defects with RTP contact firing

### 5. Conclusion

SiN<sub>x</sub>-induced hydrogen passivation of Si ribbons has been found to be most effective when the SiN<sub>x</sub> post-deposition anneal includes controlled rapid cooling and backside Al alloying. A three-step model is proposed and relates the hydrogen passivation to the release of hydrogen from the SiN<sub>x</sub> film, retention of hydrogen at defect sites, and injection of vacancies generated during Al/Si alloying. RTP contact firing was found to be more effective in preserving the hydrogen defect passivation achieved during the initial hydrogenation step and has resulted in 4-cm<sup>2</sup> screen-printed cell efficiencies as high as 14.7% on 300μm thick String Ribbon Si and 14.6% on 300 μm EFG Si.

### Acknowledgement

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### 6. References

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- [2] S. K. Estreicher, J. L. Hastings, P. A. Fedders, Mater. Sci. Eng. **B58**, 31 (1999).